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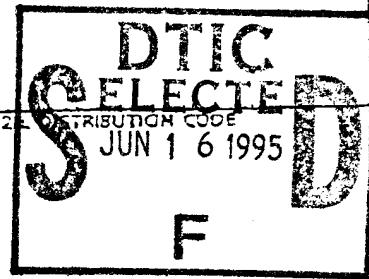
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We report here on several research projects funded by contract F49620-93-1-0153. We have continued investigations in Bayesian analysis and empirical distribution approaches for parameter estimation problems. We are also developing computational methods for simulating subsurface transport and remediation strategies of interest at AFESC, Tyndall AFB, and AL/OES, Brooks AFB.

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Statistical Techniques for Identification
and Robust Control in
Distributed Parameter Systems

Ben G. Fitzpatrick

We report here on several research projects funded by contract F49620-93-1-0153. We have continued investigations in Bayesian analysis and empirical distribution approaches for parameter estimation problems. We are also developing computational methods for simulating subsurface transport and remediation strategies of interest at AFESC, Tyndall AFB, and AL/OES, Brooks AFB.

Bayesian Methods in Identification and Control. Bayesian analysis seeks to answer statistical questions using probability measures on the parameter space, measures which represent our uncertainty in the knowledge of the parameter. Inference begins with a prior probability measure on the parameter space, and through Bayes' theorem one calculates the conditional law of the parameter, given observations of the system (the posterior distribution). Our work in this field has had two main focuses: the "large sample" behavior of the posterior distribution in identification problems and the choice of prior distributions in particular applications.

Large Sample Analysis of the Posterior. We have been investigating a Bayesian strategy for adaptive control. This method involves an expected cost, similar to LQG control, but with the expectation taken with respect to the prior distribution on the parameter space. We have devised and simulated an updating (or adaptation) technique using the posterior distribution. When measurements are taken, we update the probability distribution on the parameter space and recompute the control input. Of great interest in such a situation is the behavior of the posterior distribution as more measurements are

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incorporated.

To begin to understand the large sample behavior, we have (with G. Yin of Wayne State University) found rather general convergence results for posterior distributions in nonlinear regression problems. In particular we have found that as the sampling rate increases (over a fixed time interval), the posterior distributions concentrates at the "true" parameter at an exponential rate. The convergence rate results rely heavily on large deviation methods. The regression situation to which our results apply does not currently include the control system of interest: the measurements are required to be statistically independent. However, correlated processes can be examined in a similar manner, if the correlation is sufficiently small for measurements that are temporally far apart. Our current work is in determining if the control problem of interest here has a correlation structure for which these techniques may apply.

Prior Distributions for Estimation in Groundwater Problems. A major difficulty in the field scale simulation and (model-based) prediction of subsurface transport is the scarcity of data for a particular site. In many cases one may have as few as a dozen monitoring wells for a site on the order of tens of thousands of square meters. In such a case, estimating spatially varying parameters such as hydraulic conductivity is a very challenging problem. One must constrain the problem sufficiently well to obtain solutions to estimation criteria (e.g., maximum likelihood). On the other hand, these constraints can seem rather artificial, and must not impose too much smoothness (which is typical of many regularization methods). We are currently implementing prior distributions which involve a minimal level of smoothness. These priors were introduced by Geman and Mc-Clure within the context of image restoration, in which the function to be estimated has little structure other than regions of relative smoothness broken up by sharp edges. This is exactly the type of prior information one expects in a subsurface geological structure. Our initial computations using this method are very promising. In the test examples we

have examined (the principal investigator and his student, Julius King, who was supported on this contract), the image reconstruction method has performed at least as well as the standard kriging techniques of geostatistics, and in most cases the image reconstruction method outperformed kriging. We have applied our method to hydraulic conductivity data obtained from the MADE-2 experiments conducted at Columbus AFB, Mississippi. These experiments were conducted under the supervision of Dr. Tom Stauffer of AFESC, Tyndall AFB, who generously supplied us with data.

Recent computational investigations have focused on simultaneous estimation of hydraulic head and conductivity from the MADE field data, in a penalized least squares approach. We have worked primarily with penalty terms based on total variation methods. The advantage over the penalty of Geman and McClure is that it provides the compactness crucial for obtaining convergence results. We are in the process of performing a systematic set of computations in order to understand the impact of (1) the choice of penalty, (2) the basis functions used to approximate the conductivity, and (3) the choice of numerical optimization technique for computing the minimizer of the least squares cost.

Subsurface Contaminant Transport. We are currently investigating mathematical models for the transport of contaminants in groundwater. We are currently developing computational algorithms for contaminant transport simulation, using both spectral/ domain decomposition techniques as well as traditional finite element methods. We have applied the theoretical framework of Banks and Ito to study convergence in the parameter estimation problem. Subtleties in the analysis arise due to the need for discontinuous coefficients in the transport equation. An important question for analyzing hydrocarbon contamination of groundwater on Air Force bases is the development of models for biodegradation. Biodegradation may greatly reduce the contaminant level in some situations. Current research in this project is the development of accurate models of biodegradation, including bacteria population growth and uptake of hydrocarbons and dissolved

oxygen.

Another problem of current interest involves gas transport in the subsurface. This project was inspired by experiments conducted at Kelly AFB under the supervision of Dr. Richard Albanese of AL/OES, Brooks AFB. Electromagnetic radiation was used to heat a plume of contaminant (TCE). The liquid was boiled, the idea being that the gas would rise to the surface to be captured and disposed of. The gas in the experiment moved parallel to the surface, however, and the plume was spread horizontally. In order to understand this behavior we are analyzing models of gas transport in porous media. It is hoped that, when coupled with inverse methods for estimating transport parameters, such models will be able to provide accurate predictions so that unpredicted spreading may be avoided. It is of further interest to develop control strategies to optimize this vapor extraction process. This objective will require the coupling of electromagnetic, multi-phase transport, and thermal models.

Shape Design and Control for Smart Materials. In this project we are studying the use of piezoceramic actuators for bending a flexible body in order to match a desired shape. Applications for this work include bending flexible airfoils to achieve a specified shape as well as adjusting airfoils to the flow conditions. We have begun this project by examining the shape matching problem for a 1-d Euler-Bernoulli beam. The unboundedness of the input operator associated with piezoceramic actuators (two derivatives of a step function – the control appears as an induced bending moment) requires that the problem be formulated in the dual of the energy space. Moreover, some particular shapes may not be attainable with a given configuration of actuators. We have posed the problem as a minimum norm problem, and we developed existence and approximation results for finding control inputs. We have completed a number of computational simulations which demonstrate the feasibility of our method. We have also made some progress in the development of actuator placement strategies.

Another problem studied in this project is the estimation of parameters in nonlinear stiffness models for vibrating beams. The ability to identify changes in material properties in flexible structures is of great importance in the design of compensators. In this project we have developed numerical methods for an on-line (adaptive) scheme for estimating stiffness changes of a beam undergoing persistent excitation from piezoceramic patches. The nonlinearity involved is a piecewise linear stiffness function meant to provide a simple model of damage. The estimation scheme identifies the time at which the system becomes nonlinear and it provides an estimate of the stiffness function. Simulation studies have been very encouraging.

Summary. We have made substantial progress in several areas of proposed research, many of which have indicated further directions of study. We are continuing with the analysis and computational implmentation of Bayesian statistical methods for inverse and control problems involving uncertainty. We have made a good deal of progress in the development of models for various subsurface transport problems of interest at Tyndall and Brooks Air Force Bases. During the additional period of research (i.e., year two of the contract), we have continued developing computational models for these transport problems in support of the Air Force's need for understanding the contaminant levels on various sites of Air Force interest. A great deal of progress has been made in understanding techniques for estimation of groundwater velocity fields based on least squares estimation of head and conductivity from field data.

Papers. The following is a list of papers completed during the term of the current research grant.

1. "Shape Matching with Smart Material Structures Using Piezoceramic Actuators," by Ben G. Fitzpatrick, to appear in *J. Intell. Material Systems and Structures.*

2. "Large Sample Behavior in Bayesian Analysis of Nonlinear Regression Models," by

Ben G. Fitzpatrick and G. Yin, to appear in *J. Math. Anal. Appl.*

3. "Approximation and Parameter Estimation Problems for Algal Aggregattion Models," by A. S. Ackleh, B. G. Fitzpatrick, and T. G. Hallam, *Math. Methods and Models in Appl. Sci.*, **3**, no. 4, 1994, pp. 291-311.

4. "Homogenization of the Von Karman Plate Equations," by Ben G. Fitzpatrick and D. A. Rebnord, submitted to *Asymptotic Analysis.*

5. "Rate Distribution Modeling for Structured Heterogeneous Populations," by Ben G. Fitzpatrick, *Proceedings of the International Conference on Control of Distributed Parameter Systems,* Vorau, 1993, pp. 131-141.

6. "Analysis and Approximation for Inverse Problems in Contaminant Transport and Biodegradation Models, " by Ben G. Fitzpatrick, submitted to *J. Num. Func. Anal. Opt.*

7. "Parameter Estimation in Groundwater Flow Models with Distributed and Pointwise Observations," by Ben G. Fitzpatrick and Michael A. Jeffris, submitted to *Discrete and Continuous Dynamical Systems.*

8. "Estimation of Time Dependent Parameters in General Parabolic Evolution Systems," by A.S. Ackleh and Ben G. Fitzpatrick, submitted to *J. Math. Anal. Appl.*

9. "Estimation of Distributed Individual Rates from Aggregate Population Data," by H. T. Banks, B. G. Fitzpatrick, and Y. Zhang, submitted to *Proceedings of the International Conference on Differential Equations and Applications to Biology and Industry,* Claremont, 1994.

10. "A Comparison of Estimation Methods for Hydraulic Conductivity Functions from Field Data," by Ben G. Fitzpatrick and J. A. King, submitted to *Computation and Control IV: Proceedings of the Fourth Bozeman Conference.*

11. "Least Squares Estimation of Hydraulic Conductivity from Field Data," by Kendall R. Bailey, Ben G. Fitzpatrick, and M. A. Jeffris, submitted to 1995 ASME 15th Conference on Mechanical Vibration and Noise and Design Technical Conferences.

12. "A Bounded Variation Approach to Inverse Interferometry," by Ben G. Fitzpatrick, Stephen L. Keeling, and Stacey G. Rock, submitted to 1995 ASME 15th Conference on Mechanical Vibration and Noise and Design Technical Conferences.

13. "Convergence and Large Deviations in a Bayesian Approach to Functional Estimation Problems," by Ben G. Fitzpatrick and G. Yin, submitted to 1995 ASME 15th Conference on Mechanical Vibration and Noise and Design Technical Conferences.

14. " On Line Estimation of Stiffness in Nonlinear Beam Models with Piezoceramic Actuators," by M. A. Demetriou and B. G. Fitzpatrick, submitted to 1995 ASME 15th Conference on Mechanical Vibration and Noise and Design Technical Conferences.